Schedule Uncertainty Analysis Using Historical Data

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Outline

- Background/Purpose
- Methodology
- Data Analysis
- Simulation Models
- Results
- Conclusions

Background/Purpose

- At life cycle reviews and key decision points, NASA projects are required to provide risk-informed schedule, schedule-adjusted cost, and joint cost and schedule confidence levels.
- The Standing Review Boards (SRB) are charged with assessing the adequacy of the integrated cost and schedule estimate and funding strategy. This requires the SRB programmatic analyst to do independent cost and schedule assessments.
- As part of the independent programmatic assessment, an Independent Schedule Estimate (ISE) can be developed
- The generally accepted practice for schedule risk assessment consists of two parts:
  - Schedule uncertainty – general uncertainty about the duration of activities
  - Discrete risks – specific things that can go wrong
- There are three generally accepted methods for estimating schedule uncertainty:
  - Subject Matter Experts (SME) provide probability distribution functions (PDF)
  - Actual project performance data is used to estimate PDFs
  - Historical schedule data from similar projects is used to estimate PDFs
- This paper demonstrates a method for estimating schedule uncertainty using analogous historical data.

Methodology

- Collect top-level schedule data on major milestones for spacecraft projects
- Filter the data for analogous missions
- Calculate the duration between major milestones
- Fit PDF curves to the duration data
- Calculate the correlation between phases
- Build level 1 and level 2 simulation models
  - Level 1 = duration from PDR to Launch
  - Level 2 = sum of durations: PDR to CDR, CDR to I&T, I&T to Launch
- Run the simulation models and produce schedule s-curves

DATA ANALYSIS

Data Source

- The source of data for this study is the "Master List Project Schedule Milestones July 15, 2013" Excel file
- This file is maintained by the Cost Analysis Division (CAD) at NASA HQ.
- This file contains schedule data for major milestones for over 290 NASA projects.
- Milestones collected are: ATP, SRR, PDR, CR, CDR, I&T Start, PER, PSR, Launch, EoM, EoeM
- Only missions that have launched or plan to launch soon are included in the database. There are no cancelled projects in the data.
- For various reasons, many projects do not have a complete set of milestone dates.

Project	ATP	SRR	PDR	CR	CDR	I&T Start	PER	PSR	Launch
ACE	10/1/1993	11/1/1992	11/1/1993	9/1/1993	10/1/1994	4/24/1996	1/7/1997	6/10/1997	8/25/1997
ACRIMSAT		3/16/1996	12/1/1997		2/1/1998				12/21/1999
ACTS	8/1/1984	7/15/1985	5/15/1986		5/15/1988	6/1/1991	4/1/1992	6/1/1992	9/1/1993
AE-C	10/1/1971		2/1/1972		8/1/1972				12/13/1973
AEM-HCMM	12/1/1974								4/26/1978
AIM		5/22/2003	1/28/2004	4/28/2004	10/27/2004	10/27/2004	4/6/2006	2/26/2007	4/25/2007
AMPTE	2/1/1982				11/1/1982				8/16/1984
Apollo CSM	7/1/1962		1/6/1965		2/6/1965				10/11/1968
Apollo LEM	1/1/1963		9/1/1963		1/1/1966				3/3/1969
Aqua (PM-1)	8/1/1993		4/30/1997		6/19/1998	7/1/1998	2/16/2000	2/5/2002	5/4/2002
Aquarius		8/12/2004	5/28/2005	9/28/2005	7/21/2008	6/1/2009	6/26/2010	3/2/2011	6/9/2011
ARES I (Constellation)		12/19/2006	Delta PDR	/07	cancelled	cancelled	cancelled	cancelled	6/15/2014
Aspera-3	Instrument on Mars Express			9/5/2000	5/1/2000				6/2/2003
Astro-1	Shuttle Mission								12/2/1990
Astro-2	Shuttle Mission								3/2/1995
ASTRO-E	Failed Mission								7/10/2005
Astro-E2 / SUZAKU	07/2001		09/2001	3/2002	4/12/2002				7/9/2005
Astro-H	6/20/2008	12/15/2008	3/10-11/2010		11/16/2011	N/A	10/14/2012	4/1/2014	8/15/2015?
ATS-1	2/1964								12/7/1966
Technology Satellite)	4/1967								4/6/1967
ATS-3									11/5/1967
ATS-4									8/10/1967
(Applications Technology Sa	8/1969								8/12/1969
(Applications Technology Sa	5/1974								5/15/1974
Aura (Chem-1) or Chemistry	8/1/1993	7/1/1999	11/16/1999		9/12/2000	10/1/2001	4/2/2003	3/4/2004	7/15/2004
BARREL	12/1/2007	5/8/2008	3/26/2010	4/1/2010	1Q2011	lloon Experim	loon Experim	loon Experim	4Q2013
CALIPSO	12/1/1998	1/15/2000	9/18/2000	9/15/2000	4/15/2003	3/1/2004	8/1/2004	5/19/2005	4/28/2006
Cassini	1/1/1990	8/1/1988	8/11/1992		12/9/1992				10/15/1997
Chandra	1/1/1989	12/1/1992	11/1/1994		2/1/1996	10/1/1997	10/1/1998	2/4/1999	7/23/1999
CHIPSAT		9/1/1999	9/1/2000	12/1/2000	4/18/2001	6/1/2002	8/15/2002	10/6/2002	1/12/2003
CINDI		5/10/2000	6/19/2001	11/14/2001	6/25/2002				4/16/2008
Clark	Cancelled		Cancelled						
CLARREO	2/1/2011	ended Pre-Pha	TBD		TBD	TBD		TBD	TBD
Clementine	2/15/1992	6/15/1992	9/15/1992		12/15/1992				1/25/1994
CloudSat	4/1/1999	2/29/2000	9/1/2000	11/15/2000	8/1/2001			7/1/2004	4/28/2006
Cluster		9/1/1989							6/4/1996
Cluster-2 (Rumba & Tengo)	one of two laun	9/1/1989	ATP immediately after Cluster 1 destroyed at launch. These are Replicas						8/9/2000
Cluster-2 (Salsa & Samba)	one of two laun	9/1/1989	ATP immediately after Cluster 1 destroyed at launch. These are Replicas						7/16/2000
COBE	7/1/1982	7/15/1982	10/11/1983		5/1/1987	9/1/1988	12/1/1988	9/15/1989	11/18/1989
CONTOUR	10/1/1997	5/19/1999	1/19/2000	2/3/2000	12/12/2000	2/1/2002	1/8/2002	4/19/2002	7/3/2002
Constellation Integration		11/14/2006	3/4-5/2010 DR: 6/18/200		cancelled	cancelled	cancelled	cancelled	

Data Filtering

- The schedule database was filtered for projects with the theme “Planetary” or “Planetary (Mars).”
- Projects that do not have PDR or Launch dates are excluded.
- Galileo was excluded because it was twice as long as any other project due to delays related to the Space Shuttle Challenger disaster.
- Redundant data points are excluded (e.g. Viking Lander B, Viking Orbiter).

Selected Missions

- Cassini
- CONTOUR
- DAWN
- Deep Impact
- Genesis
- GRAIL
- JUNO
- LADEE
- Lunar Prospector
- MAGELLAN
- Mars Express
- Mars Observer
- Mars Odyssey 01
- Mars Pathfinder
- Mars Polar Lander (MPL)
- MAVEN
- MCO
- MER-A (SPIRIT)
- MER-B (Opportunity)
- MESSENGER
- MGS
- MMM (M3) on Chandrayaan-1
- MRO
- MSL
- NEAR
- New Horizons
- OSIRIS-REX
- Phoenix
- STARDUST
- Ulysses
- Viking Lander A
- Voyager 1

Data Set

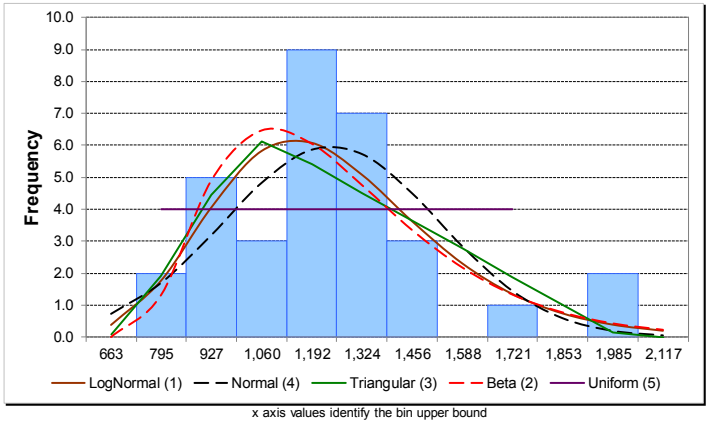
Observations	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5	Variable 6	Variable 7	Variable 8	Variable 9	Variable 10	Variable 11
Variable ID	DaysATPtoSRR	DaysSRRtoPDR	DaysPDRtoCDR	DaysCDRtoI&T	DaysI&TtoLaunch	DaysATPto Launch	DaysSRRto Launch	DaysPDRto Launch	DaysCDRto Launch	DaysI&TtoL aunchNoOu tliers	DaysPDRto LaunchNoO utliers
Cassini		1471	120			2844	3362	1891	1771		
CONTOUR	595	245	328	416	152	1736	1141	896	568		896
DAWN		198	245	217	980		1640	1442	1197		
Deep Impact		285	339	468	609		1701	1416	1077	609	
Genesis	142	119	331	138	646	1376	1234	1115	784	646	1115
GRAIL		317	364	255	411		1347	1030	666	411	1030
JUNO		897	342	346	491	2076	2076	1179	837	491	1179
LADEE		366	299				1482	1116	817		1116
Lunar Prospector			92			1011		875	783		875
MAGELLAN		536	397			2012	2212	1676	1279		
Mars Express			90					1217	1127		1217
Mars Observer		2632	504		1304	2308	3861	1229	725		1229
Mars Odyssey 01		130	186				1041	911	725		911
Mars Pathfinder		261	414			1160	1494	1233	819		1233
Mars Polar Lander (MPL)		111	581				1404	1293	712		1293
MAVEN	310	339	364	350	511	1874	1564	1225	861	511	1225
MCO		245	447				1371	1126	679		1126
MER-A (SPIRIT)		97	310	186	470		1063	966	656	470	966
MER-B (Opportunity)		97	310	221	463		1091	994	684	463	994
MESSENGER	153	387	299	292	576	1707	1554	1167	868	576	1167
MGS	56	155	251			996	940	785	534		785
MMM (M3) on Chandrayaan-1		48	256	457	434		1195	1147	891	434	1147
MRO	106	190	302	329	484	1411	1305	1115	813	484	1115
MSL	223	192	346	274	1365	2400	2177	1985	1639		
NEAR			219	186	258	869		663	444		663
New Horizons		160	374				1345	1185	811		1185
OSIRIS-REX	353	296	406	307	579	1941	1588	1292	886	579	1292
Phoenix		349	252	147	481		1229	880	628	481	880
STARDUST	106	192	264	205	397	1164	1058	866	602	397	866
Ulysses	379	2725	457			4388	4009	1284	827		1284
Viking Lander A			670			1967		1419	749		
Voyager 1		1189	271			2043	2258	1069	798		1069

Data Analysis – Curve Fitting Methodology

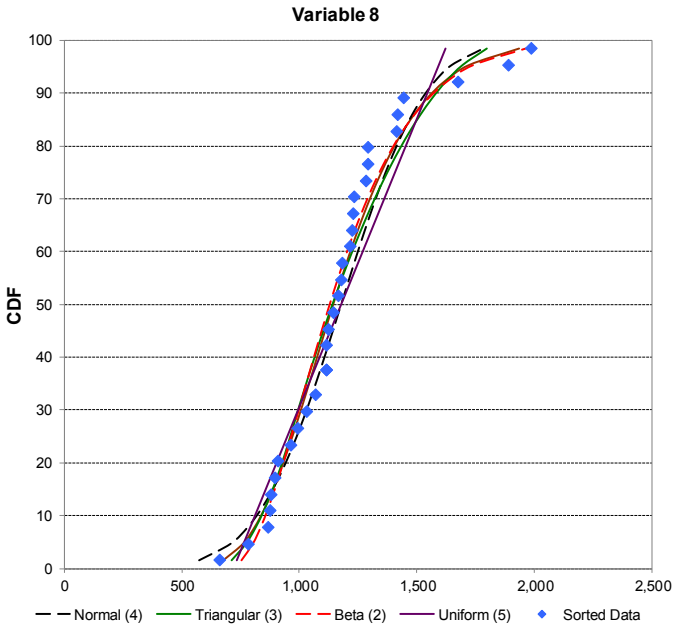
- Calculate calendar days duration between major milestones:
  - Days from PDR to Launch
  - Days from PDR to CDR
  - Days from CDR to I&T Start
  - Days from I&T Start to Launch
- Using a statistical data analysis tool called CO$TAT, find the distribution shape that most closely matches the data.
- Lognormal, Normal, Triangular, Beta and Uniform distributions are assessed against the selected data.
- The sum of squared error (SSE) method was used to fit the distributions to the data set.

Curve Fit - PDR to Launch

	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	1,177.7188	1,178.4256	1,177.7140	1,177.8790	1,179.4018	1,177.7187
StdDev	290.4668	291.7406	280.3910	277.4916	288.1516	264.5037
CV	0.2466	0.2476	0.2381	0.2356	0.2443	0.2246
Min	663.0000			628.7257	670.4596	719.5849
Mode	1,115.0000	1,077.8320	1,177.7140	966.8299	1,016.8908	
Max	1,985.0000			1,938.0815	6,689.0033	1,635.8526
Alpha					2.7712	
Beta					30.0000	
Data Count	32	% < 0 =	0.00%	None	None	None
Standard Error of Estimate		55.8306	81.1819	77.8472	57.7336	112.4435
Rank		1	4	3	2	5
SEE / Fit Mean		4.74%	6.89%	6.61%	4.90%	9.55%
Chi^2 Fit test 8 Bins, Sig 0.05		Good (16%)	Good (42%)	Good (16%)	Good (48%)	Good (6%)



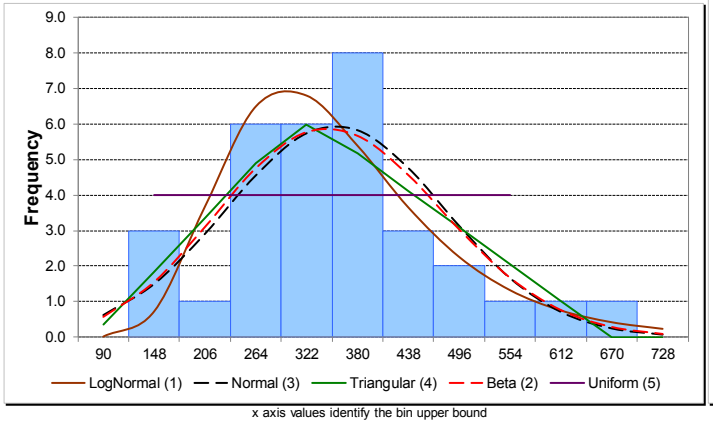
x axis values identify the bin upper bound



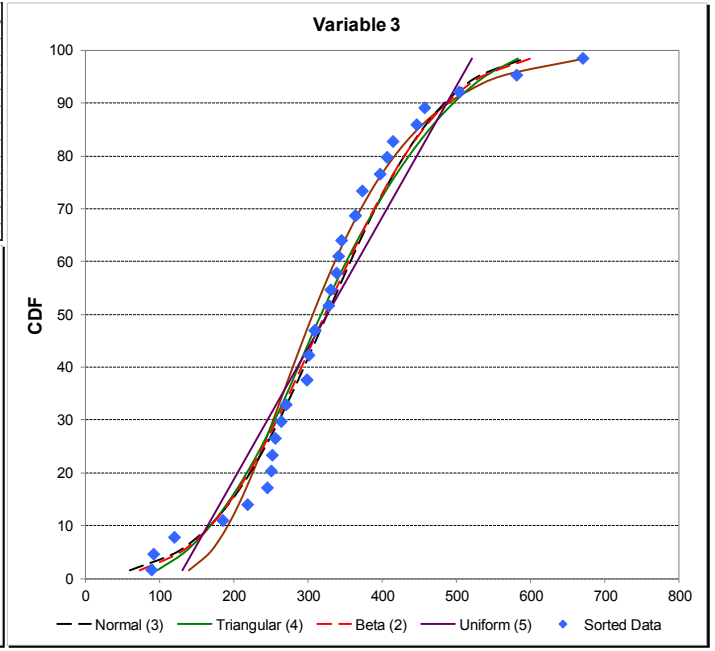
SPECIFICATION	
Variable	Variable 8
ID	DaysPDRtoLaun
Percentile	AutoCalc
Min Method	SSE
Min On	Values
Weighting	None
Filter	None
MEAN = SAMPLE MEAN	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
STDEV = SAMPLE STDEV	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
LOW BOUNDS	
LogNormal	N/A
Normal	Unconstrained
Triangular	Unconstrained
Beta	Unconstrained
Uniform	Unconstrained
SURROUND	
LogNormal	N/A
Normal	N/A
Triangular	Off
Beta	Off
Uniform	Off

Curve Fit - PDR to CDR

	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	325.9375	327.6903	325.9386	325.9688	325.8424	325.9375
StdDev	125.4658	123.6420	123.3971	121.0827	123.3159	116.1943
CV	0.3849	0.3773	0.3786	0.3715	0.3785	0.3565
Min	90.0000			50.2655	-348.3794	124.6831
Mode	299.0000	268.3835	325.9386	287.8747	316.4153	
Max	670.0000			639.7663	1,435.6466	527.1919
Alpha					18.2178	
Beta					29.9874	
Data Count	32	% < 0 =	0.41%	None	0.19%	None
Standard Error of Estimate		24.6481	25.7159	28.6986	25.5153	43.4418
Rank		1	3	4	2	5
SEE / Fit Mean		7.52%	7.89%	8.80%	7.83%	13.33%
Chi^2 Fit test 8 Bins, Sig 0.05		Good (42%)	Good (36%)	Good (48%)	Good (32%)	Good (16%)



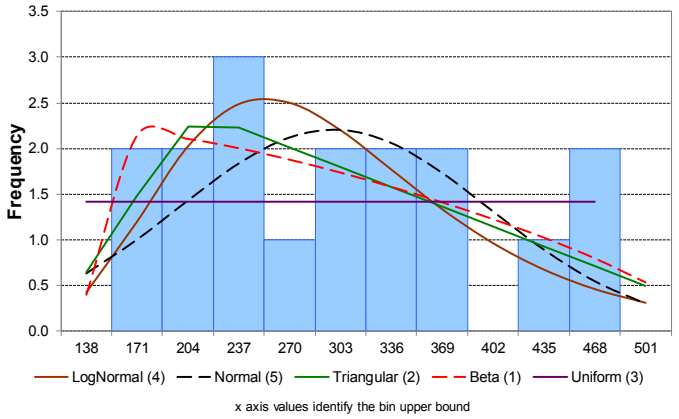
x axis values identify the bin upper bound



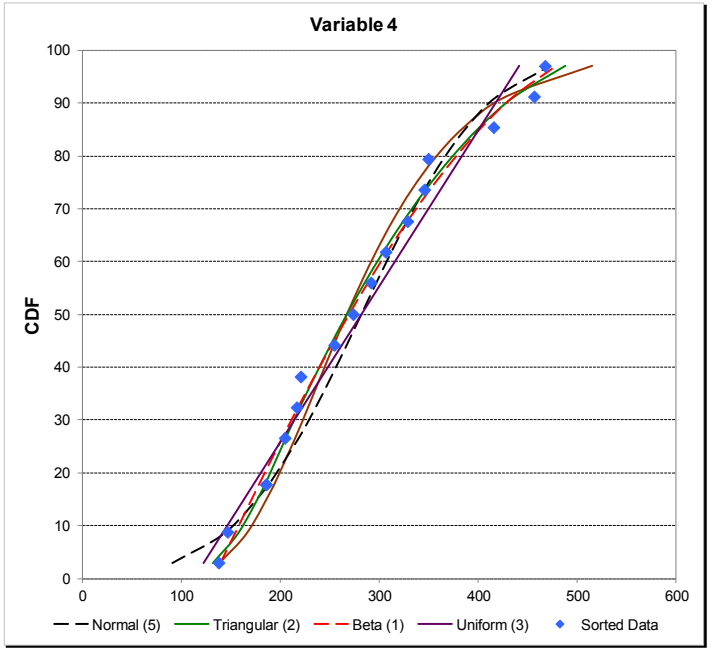
SPECIFICATION	
Variable	Variable 3
ID	DaysPDRtoCDR
Percentile	AutoCalc
Min Method	SSE
Min On	Values
Weighting	None
Filter	None
MEAN = SAMPLE MEAN	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
STDEV = SAMPLE STDEV	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
LOW BOUNDS	
LogNormal	N/A
Normal	Unconstrained
Triangular	Unconstrained
Beta	Unconstrained
Uniform	Unconstrained
SURROUND	
LogNormal	N/A
Normal	N/A
Triangular	Off
Beta	Off
Uniform	Off

Curve Fit – CDR to I&T Start

	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	282.0000	283.9363	281.9280	282.1381	282.2157	282.0000
StdDev	102.1310	101.6207	100.9969	99.7265	99.1920	97.7762
CV	0.3622	0.3579	0.3582	0.3535	0.3515	0.3467
Min	138.0000			95.8465	131.4748	112.6466
Mode	186.0000	236.9758	281.9280	191.8614	156.5016	
Max	468.0000			558.7064	526.7032	451.3534
Alpha					1.0472	
Beta					1.6985	
Data Count	17	% < 0 =	0.26%	None	None	None
Standard Error of Estimate		19.8923	20.7527	12.1107	11.9985	18.4926
Rank		4	5	2	1	3
SEE / Fit Mean		7.01%	7.36%	4.29%	4.25%	6.56%
Chi^2 Fit test 6 Bins, Sig 0.05		Good (64%)	Good (49%)	Good (21%)	Good (32%)	Good (49%)



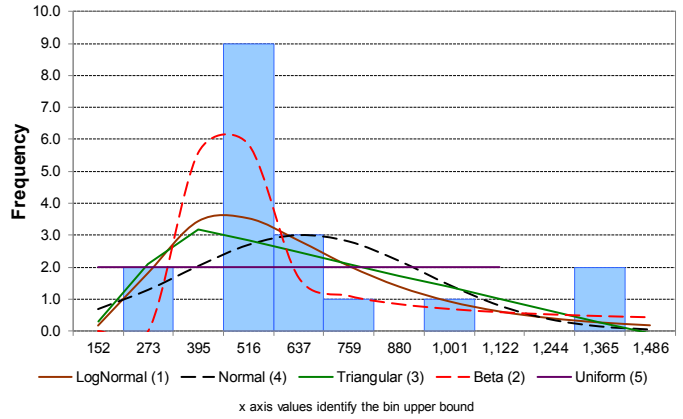
x axis values identify the bin upper bound

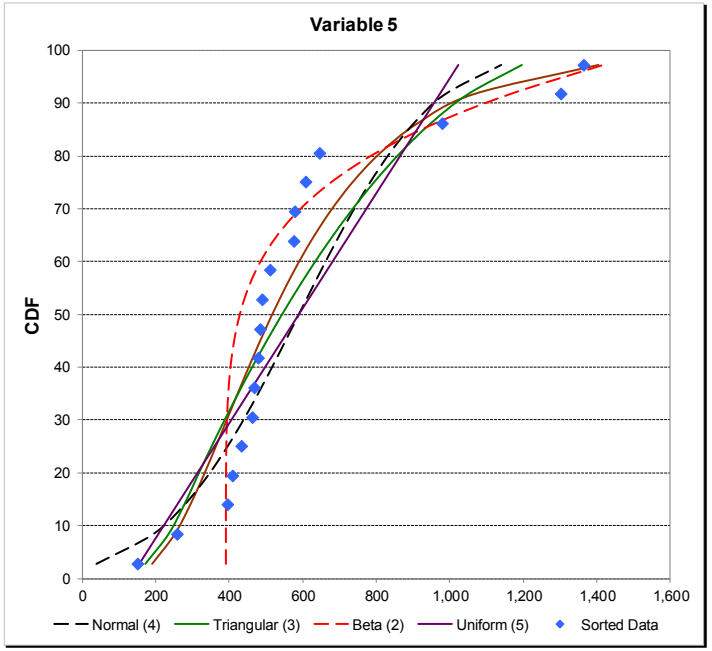


SPECIFICATION	
Variable	Variable 4
ID	DaysCDRtoI&T
Percentile	AutoCalc
Min Method	SSE
Min On	Values
Weighting	None
Filter	None
MEAN = SAMPLE MEAN	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
STDEV = SAMPLE STDEV	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
LOW BOUNDS	
LogNormal	N/A
Normal	Unconstrained
Triangular	Unconstrained
Beta	Unconstrained
Uniform	Unconstrained
SURROUND	
LogNormal	N/A
Normal	N/A
Triangular	Off
Beta	Off
Uniform	Off

Curve Fit – I&T Start to Launch

	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	589.5000	592.7094	589.5000	590.0521	590.1902	589.5000
StdDev	319.1637	331.6551	287.6735	288.4371	298.2548	265.3791
CV	0.5414	0.5596	0.4880	0.4888	0.5054	0.4502
Min	152.0000			86.7438	391.0956	129.8498
Mode		393.9062	589.5000	285.6610		
Max	1,365.0000			1,397.7515	1,562.9700	1,049.1502
Alpha					0.2000	
Beta					0.9772	
Data Count	18	% < 0 =	2.02%	None	None	None
Standard Error of Estimate		98.3849	146.5231	133.0706	105.2432	171.0182
Rank		1	4	3	2	5
SEE / Fit Mean		16.60%	24.86%	22.55%	17.83%	29.01%
Chi^2 Fit test 6 Bins, Sig 0.05		Poor (3%)	Poor (3%)	Poor (1%)	Poor (0%)	Poor (1%)



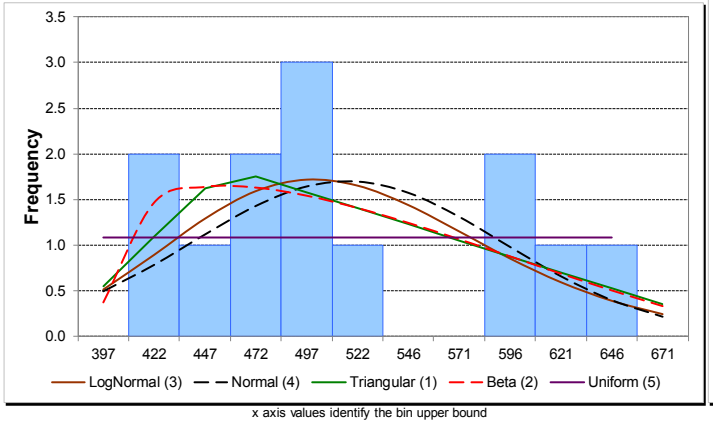


SPECIFICATION	
Variable	Variable 5
ID	DaysI&TtoLaunc
Percentile	AutoCalc
Min Method	SSE
Min On	Values
Weighting	None
Filter	None
MEAN = SAMPLE MEAN	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
STDEV = SAMPLE STDEV	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
LOW BOUNDS	
LogNormal	N/A
Normal	Unconstrained
Triangular	Unconstrained
Beta	Unconstrained
Uniform	Unconstrained
SURROUND	
LogNormal	N/A
Normal	N/A
Triangular	Off
Beta	Off
Uniform	Off

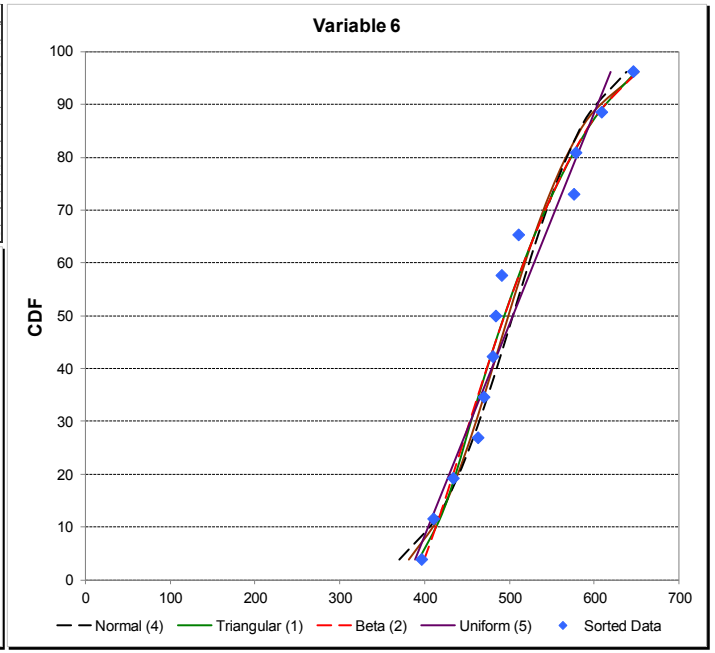
Curve Fit – I&T Start to Launch – No Outliers

- I&T to Launch exhibited poor fit characteristics, so 5 extreme data points were removed and another distribution was calculated

	Sample	LogNormal	Normal	Triangular	Beta	Uniform
Mean	504.0000	504.5063	504.0000	504.1704	504.3960	504.0000
StdDev	76.9090	76.9413	75.6320	74.2609	74.1818	72.0657
CV	0.1526	0.1525	0.1501	0.1473	0.1471	0.1430
Min	397.0000			359.1930	387.5126	379.1786
Mode		487.4032	504.0000	445.0375	443.4828	
Max	646.0000			708.2806	728.5443	628.8214
Alpha					1.2890	
Beta					2.4719	
Data Count	13	% < 0 =	0.00%	None	None	None
Standard Error of Estimate		15.0928	17.9827	13.5439	14.6345	18.7434
Rank		3	4	1	2	5
SEE / Fit Mean		2.99%	3.57%	2.69%	2.90%	3.72%
Chi^2 Fit test 6 Bins, Sig 0.05		Good (37%)	Good (53%)	Good (8%)	Poor (3%)	Good (17%)



x axis values identify the bin upper bound



SPECIFICATION	
Variable	Variable 6
ID	Daysl&TtoLaunc
Percentile	AutoCalc
Min Method	SSE
Min On	Values
Weighting	None
Filter	None
MEAN = SAMPLE MEAN	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
STDEV = SAMPLE STDEV	
LogNormal	Off
Normal	Off
Triangular	Off
Beta	Off
Uniform	Off
LOW BOUNDS	
LogNormal	N/A
Normal	Unconstrained
Triangular	Unconstrained
Beta	Unconstrained
Uniform	Unconstrained
SURROUND	
LogNormal	N/A
Normal	N/A
Triangular	Off
Beta	Off
Uniform	Off

Summary of Selected Distributions

	Days PDR to Launch	Days PDR to CDR	Days CDR to I&T	Days I&T to Launch	Days I&T to Launch No Outliers
Distribution	**LogNormal**	**LogNormal**	**Triangular**	**LogNormal**	**LogNormal**
Mean	1,178	328	282	593	505
StdDev	292	124	100	332	77
CV	0.25	0.38	0.35	0.56	0.15
Min			96		
Mode	1,078	268	192	394	487
Max			559		
Alpha					
Beta					
Data Count	32	32	17	18	13
Standard Error of Estimate	56	25	12	98	15
Rank	1	1	2	1	3
SEE / Fit Mean	4.74%	7.52%	4.29%	16.60%	2.99%
Chi^2 Fit test 8 Bins, Sig 0.05	Good (16%)	Good (42%)	Good (21%)	Poor (3%)	Good (37%)

- LogNormal distribution was selected for all phases except CDR to I&T

Correlation Matrix

Pairwise Variable Analysis For Dataset New Dataset

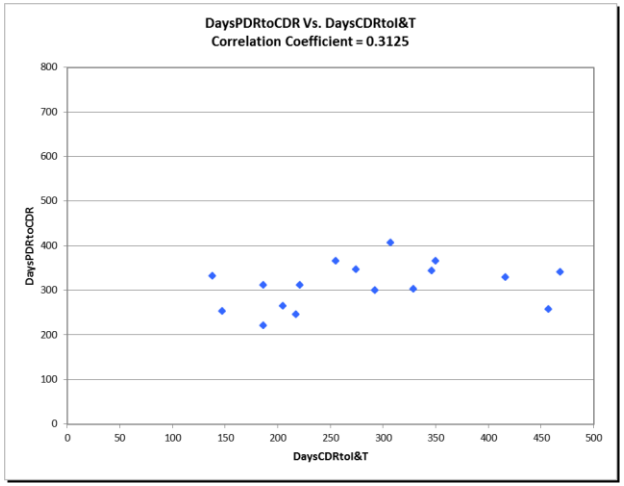
Thursday, 05 September 2013, 10:48 am

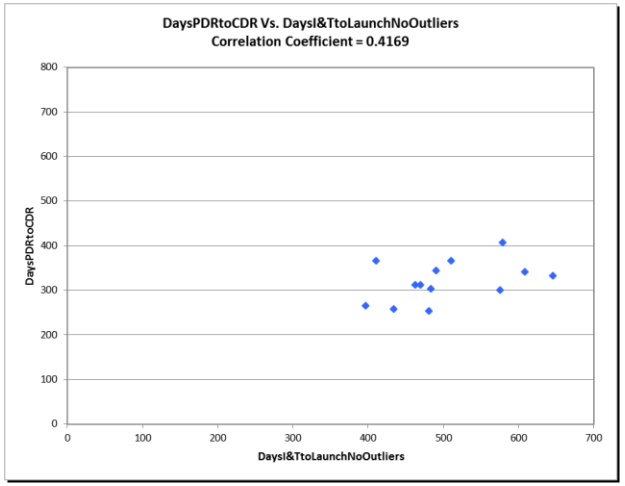
I. Correlation Matrix

	DaysATPtoSRR	DaysSRRtoPDR	DaysPDRtoCDR	DaysCDRtoI&T	DaysI&TtoLaunch	DaysATPtoLaunch	DaysSRRtoLaunch	DaysPDRtoLaunch	DaysCDRtoLaunch	DaysI&TtoLaunchNoOutliers	DaysPDRtoLaunchNoOutliers
DaysATPtoSRR	1.0000	0.3227	0.6081	0.7141	-0.3414	0.4700	0.3192	0.0930	-0.0222	0.2837	0.2413
DaysSRRtoPDR	0.3227	1.0000	0.2363	0.1733	0.5114	0.7876	0.9394	0.2284	0.1453	0.0755	0.2530
DaysPDRtoCDR	0.6081	0.2363	1.0000	0.3125	0.4750	0.3293	0.2336	0.2371	-0.1966	0.4169	0.5421
DaysCDRtoI&T	0.7141	0.1733	0.3125	1.0000	-0.1203	0.5614	0.2693	0.2863	0.2479	0.0791	0.4434
DaysI&TtoLaunch	-0.3414	0.5114	0.4750	-0.1203	1.0000	0.7104	0.7670	0.7884	0.7192	1.0000	0.6365
DaysATPtoLaunch	0.4700	0.7876	0.3293	0.5614	0.7104	1.0000	0.8592	0.5695	0.4558	0.2416	0.5807
DaysSRRtoLaunch	0.3192	0.9394	0.2336	0.2693	0.7670	0.8592	1.0000	0.5482	0.4577	0.4048	0.4556
DaysPDRtoLaunch	0.0930	0.2284	0.2371	0.2863	0.7884	0.5695	0.5482	1.0000	0.9059	0.6574	1.0000
DaysCDRtoLaunch	-0.0222	0.1453	-0.1966	0.2479	0.7192	0.4558	0.4577	0.9059	1.0000	0.6274	0.7703
DaysI&TtoLaunchNoOutliers	0.2837	0.0755	0.4169	0.0791	1.0000	0.2416	0.4048	0.6574	0.6274	1.0000	0.6574
DaysPDRtoLaunchNoOutliers	0.2413	0.2530	0.5421	0.4434	0.6365	0.5807	0.4556	1.0000	0.7703	0.6574	1.0000

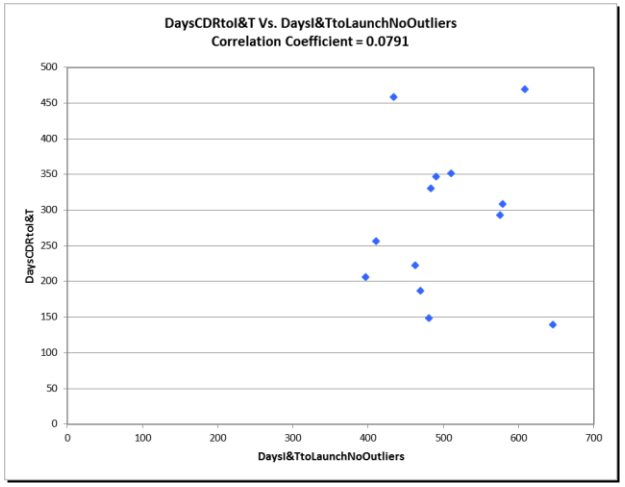
- The report shows a correlation matrix for all the data points in the data set.
- The numbers that are highlighted represent the correlation between phases of interest for this project.
- For example, for the data above, we want to know the correlation between PDR to CDR, CDR to I&T, and I&T to Launch.

Correlation Scatter Plots





- The scatter plots show that weak correlation exists between phases.



Examination of Possible Outliers

MSL

1st longest duration from PDR to Launch (1985 days, 64 months).

Removing this data point would reduce mean PDR-Launch duration by 26 days.

By November 2008 most hardware and software development was complete, and testing continued. At this point, cost overruns were approximately $400 million. In the attempts to meet the launch date, several instruments and a cache for samples were removed and other instruments and cameras were simplified to simplify testing and integration of the rover. The next month, NASA delayed the launch to late 2011 because of inadequate testing time. Eventually the costs for developing the rover did reach $2.47 billion, that for a rover that initially had been classified as a medium-cost mission with a maximum budget of $650 million, yet NASA still had to ask for an additional $82 million to meet the planned November launch.

Cassini

2rd longest duration from PDR to Launch (1891 days, 61 months).

Removing this data point would reduce mean PDR-Launch duration by 23 days.

"The spacecraft was originally planned to be the second three-axis stabilized, RTG-powered Mariner Mark II, a class of spacecraft developed for missions beyond the orbit of Mars. Cassini was developed simultaneously with the Comet Rendezvous Asteroid Flyby (CRAF) spacecraft, but various budget cuts and rescopings of the project forced NASA to terminate CRAF development in order to save Cassini. As a result, the Cassini spacecraft became a more specialized design, canceling the implementation of the Mariner Mark II series."

MAGELLAN

3rd longest duration from PDR to Launch (1676 days, 54 months).

Removing this data point would reduce mean PDR-Launch duration by 16 days.

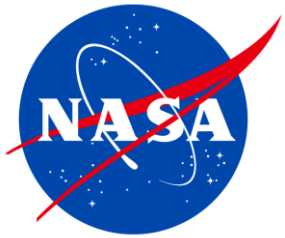
"Originally, Magellan had been scheduled for launch in 1988 with a trajectory lasting six months. However, due to the Space Shuttle Challenger disaster in 1986, several missions, including Galileo and Magellan, were deferred until shuttle flights resumed in September 1988. Intended to be launched with a new, liquid-fueled, Centaur-G shuttle deployable upper-stage booster, subsequently canceled after the Challenger disaster, Magellan had to be modified to attach to a less powerful solid-fueled, Inertial Upper Stage. The next best opportunity for launch would occur in October 1989.Further complicating the launch however, was the upcoming Galileo mission to Jupiter, which included a flyby of Venus. Intended for launch in 1986, the pressures to ensure a launch for Galileo in 1989, mixed with a short launch-window necessitating a mid-October launch, resulted in replanning the Magellan mission. Weary of rapid shuttle launches, the decision was made to launch Magellan in May 1989, and into an orbit that would require 1 year and 3 months before encountering Venus."

Dawn

4th longest duration from PDR to Launch (1442 days, 46 months).

Removing this data point would reduce mean PDR-Launch duration by 9 days.

"The status of the Dawn mission changed several times. The project was cancelled in December 2003 and then reinstated in February 2004. In October 2005, work on Dawn was placed in ""stand down"" mode, and in January 2006, the mission was discussed in the press as ""indefinitely postponed"", even though NASA had made no new announcements regarding its status. On March 2, 2006, Dawn was again cancelled by NASA. The spacecraft's manufacturer, Orbital Sciences Corporation, appealed NASA's decision, offering to build the spacecraft at cost, forgoing any profit in order to gain experience in a new market field. NASA then put the cancellation under review, and on March 27, 2006, it was announced that the mission would not be cancelled after all. In the last week of September 2006, the Dawn mission's instrument payload integration reached full functionality. Although originally projected to cost US$373 million, cost overruns inflated the final cost of the mission to US$446 million in 2007."



SIMULATION MODELS

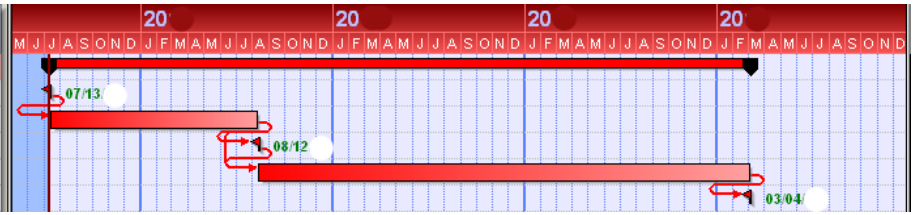
Simulation Methodology

- Build top-level schedule simulation model in Primavera Risk Analysis (PRA)
- Apply deterministic duration estimates based on nominal plan
- Apply fitted duration distributions to the phases in the model
- Apply correlation
- Run Monte Carlo Simulation
- Plot resulting s-curves, confidence level in deterministic plan, 50% confidence level
- Note that since distributions are based on actual historical durations, no additional discrete risks are applied to this model

Level 1 Models

- Level 1 Model consists of two activities:
  - ATP to PDR, Phase A & B (completed)
  - PDR to Launch, Phase C & D (historical uncertainty applied)
- Level 1 Model Variants
  - PDR to Launch distribution based on actual historical data
  - PDR to Launch distribution based on fitted Lognormal distribution
  - PDR to Launch distribution based on actuals < 1300 days PDR to Launch (4 outliers removed)

ID	Description	Remaining Duration	Start	Finish	Remaining Cost
0070	Level 1 Model, Fitted	1331	07/13	03/04	$0
0080	ATP	0	07/13		$0
0090	Sunk - ATP to PDR	395	07/13	08/11	$0
0100	PDR	0	08/12		$0
0110	PDR to Launch	935	08/12	03/03	$0
0120	Launch	0	03/04		$0

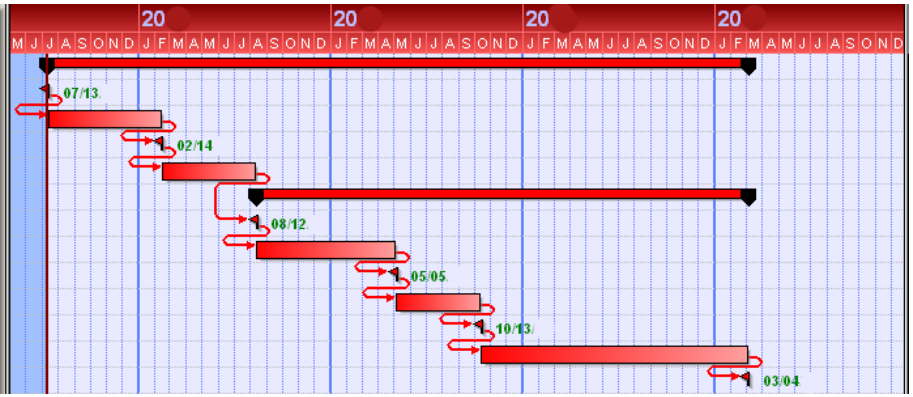


Level 2 Models

- Level 2 Model consists of 5 activities
  - ATP to SRR, Phase A (completed)
  - SRR to PDR, Phase B (completed)
  - PDR to CDR, Phase C1
  - CDR to I&T Start, Phase C2
  - I&T Start to Launch, Phase D

- Level 2 Model Variants
  - Fitted Distributions, With correlation, no I&T outliers
  - Fitted Distributions, No correlation, no I&T outliers
  - Fitted Distributions, With correlation, I&T outliers
  - Fitted Distributions, No correlation, I&T outliers
  - Actual Distributions, With correlation
  - Actual Distributions, No correlation

ID	Description	Remaining Duration	Start	Finish	Remaining Cost
0390	Level 2 Model, w Corr	1331	07/13	03/04	$0
0400	ATP	0	07/13		$0
0410	Phase A	216	07/13	02/13	$0
0420	SRR	0	02/14		$0
0430	Phase B	179	02/14	08/11	$0
0440	PDR to Launch	936	08/12	03/04	$0
0450	PDR	0	08/12		$0
0460	Phase C1	266	08/12	05/04	$0
0470	CDR	0	05/05		$0
0480	Phase C2	161	05/05	10/12	$0
0490	I&T Start	0	10/13		$0
0500	Phase D	508	10/13	03/03	$0
0510	Launch	0	03/04		$0



Correlation Factors

Model with I&T outliers

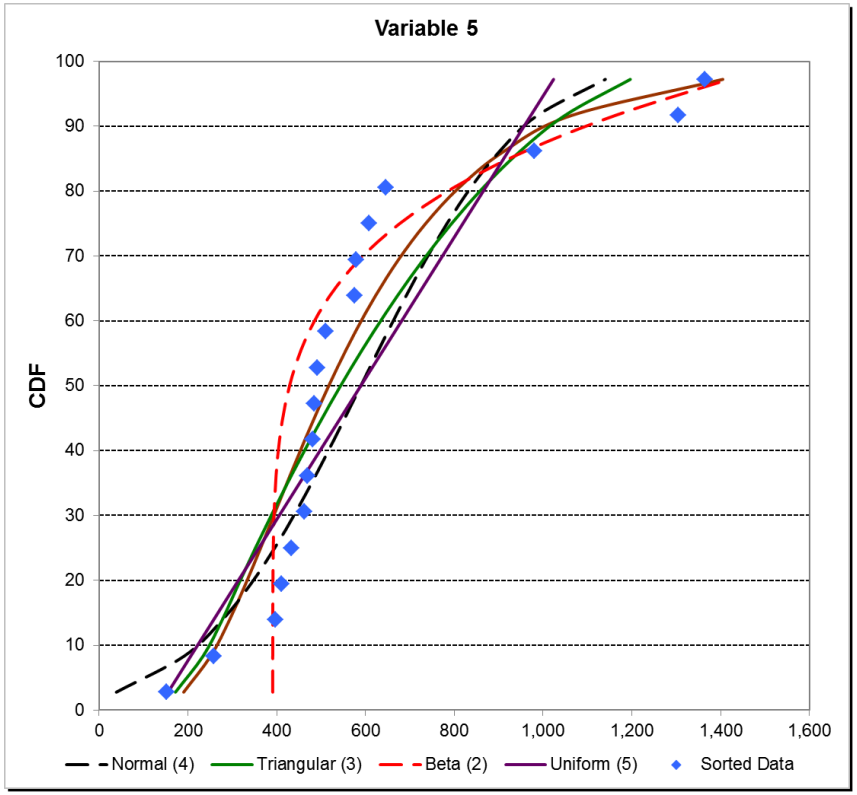
	Phase C1	Phase C2	Phase D
Phase C1	1	31%	48%
Phase C2		1	-12%
Phase D			1

Model without I&T outliers

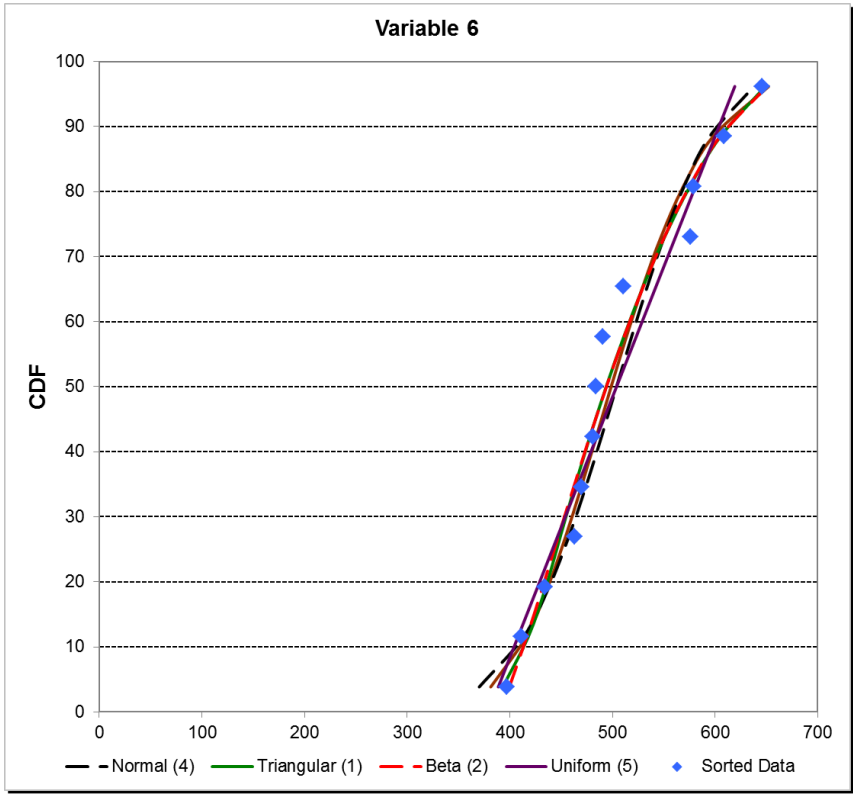
	Phase C1	Phase C2	Phase D
Phase C1	1	31%	42%
Phase C2		1	8%
Phase D			1

I&T Outliers

With I&T Outliers

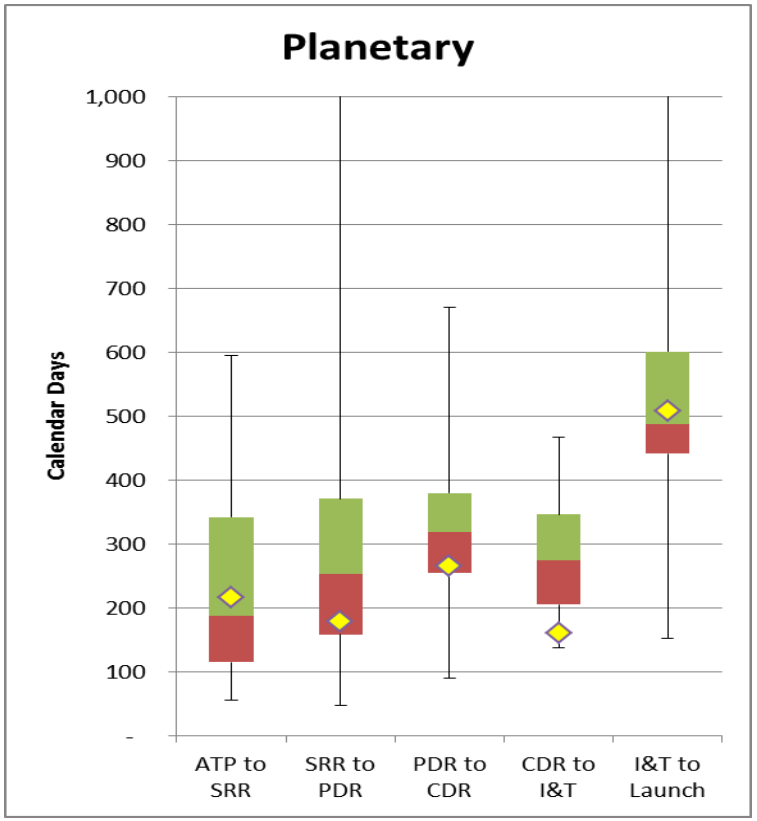


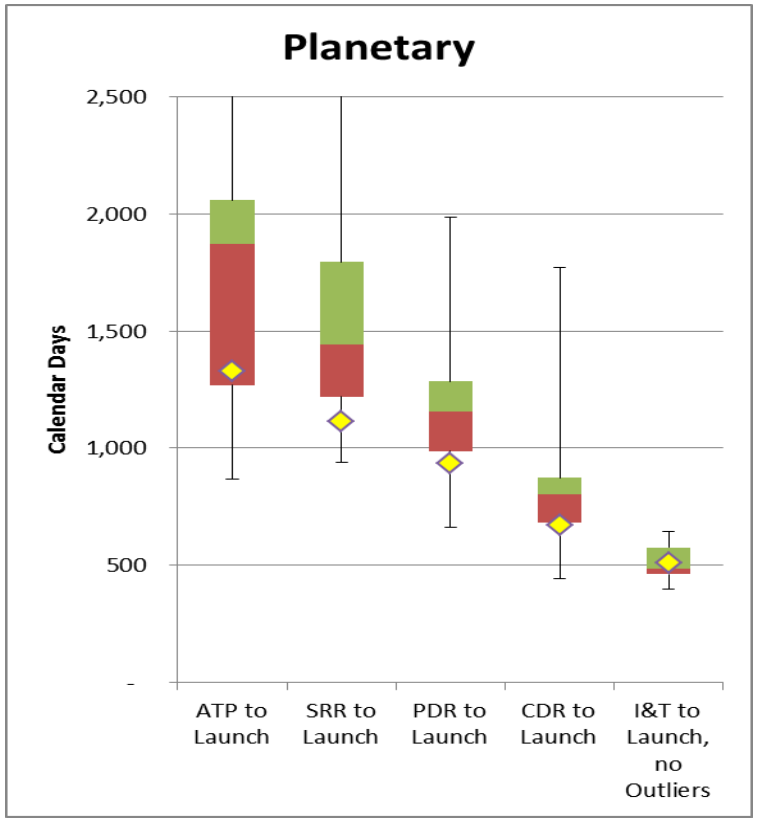
I&T Outliers Removed



RESULTS

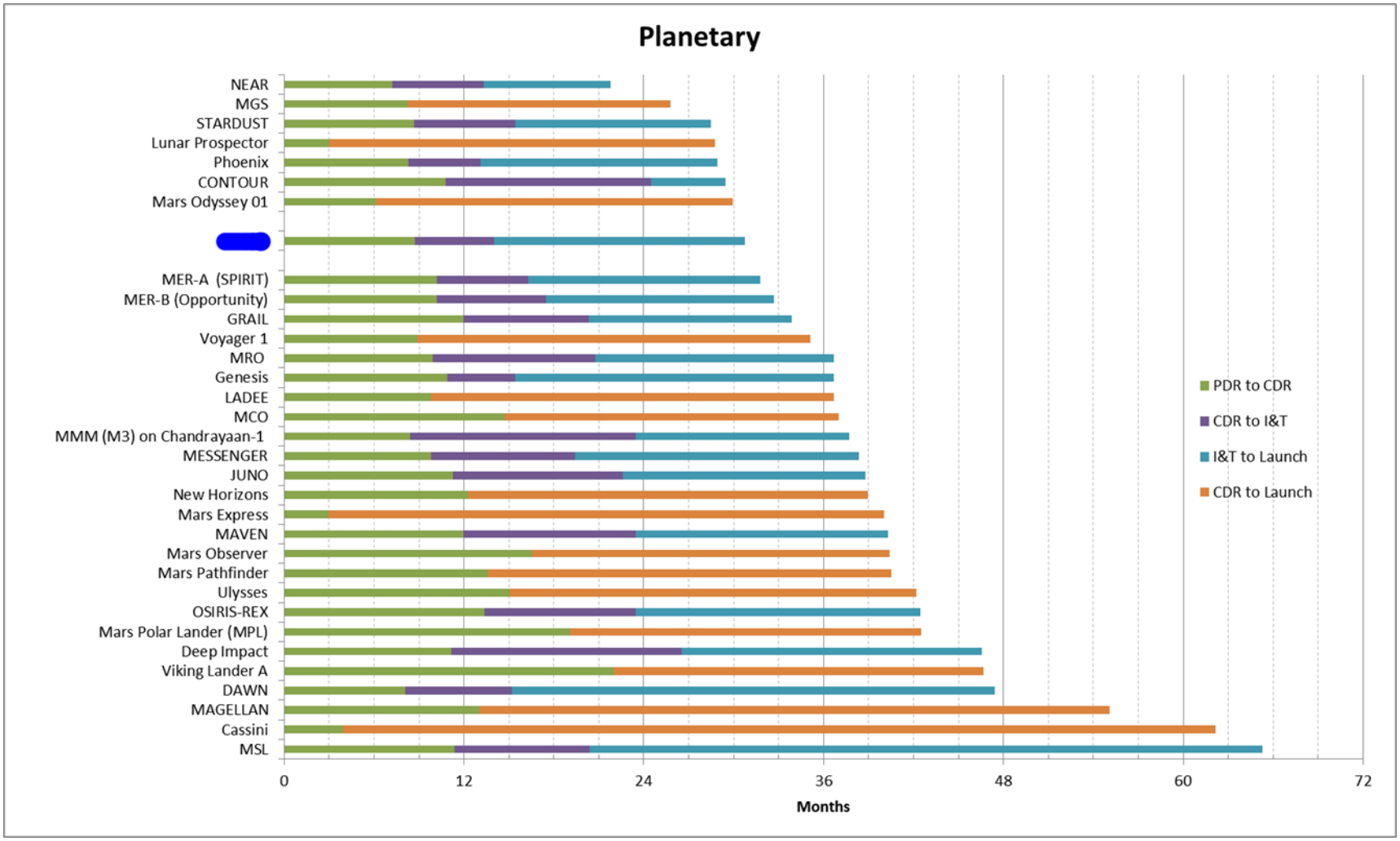
Comparative Analysis
Box & Whiskers Charts



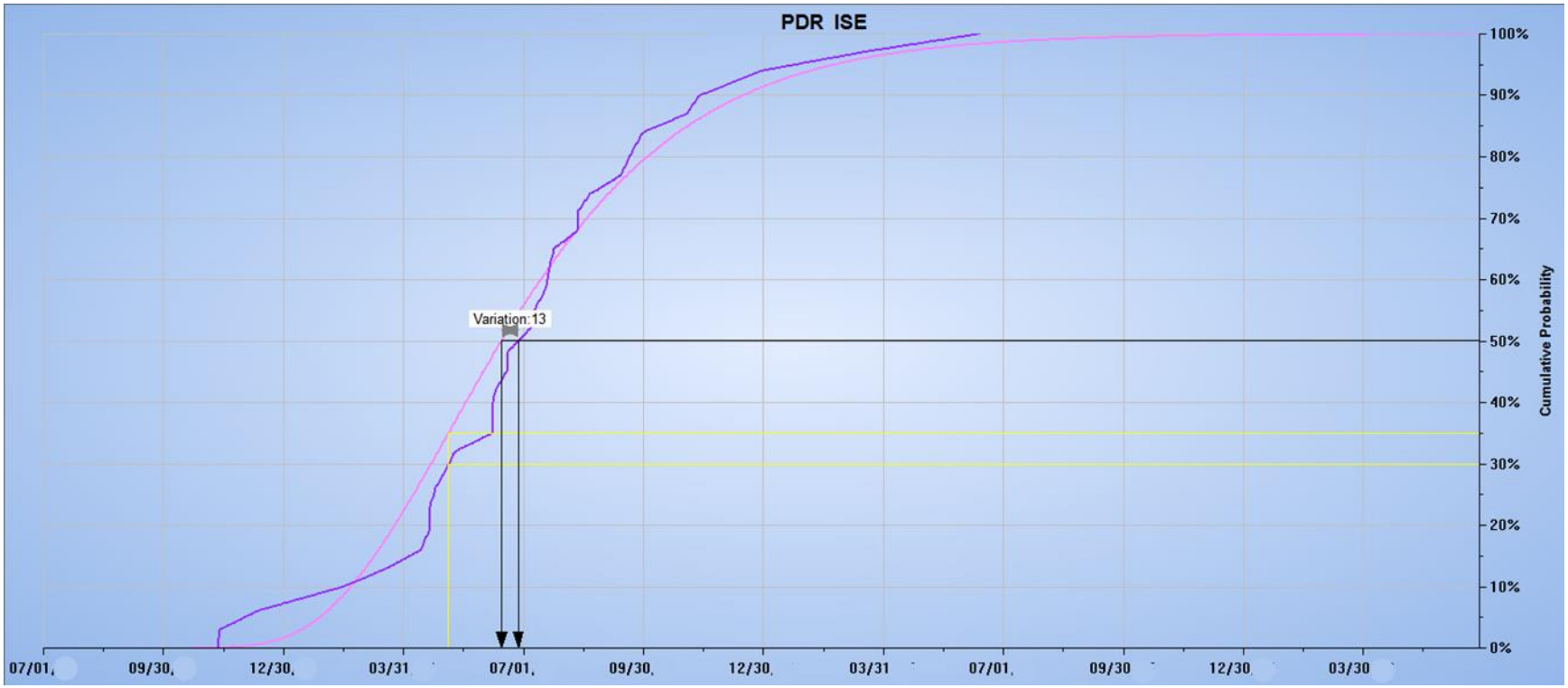


- The box and whiskers show quartile ranges.
- The yellow diamond is the hypothetical project planned duration.

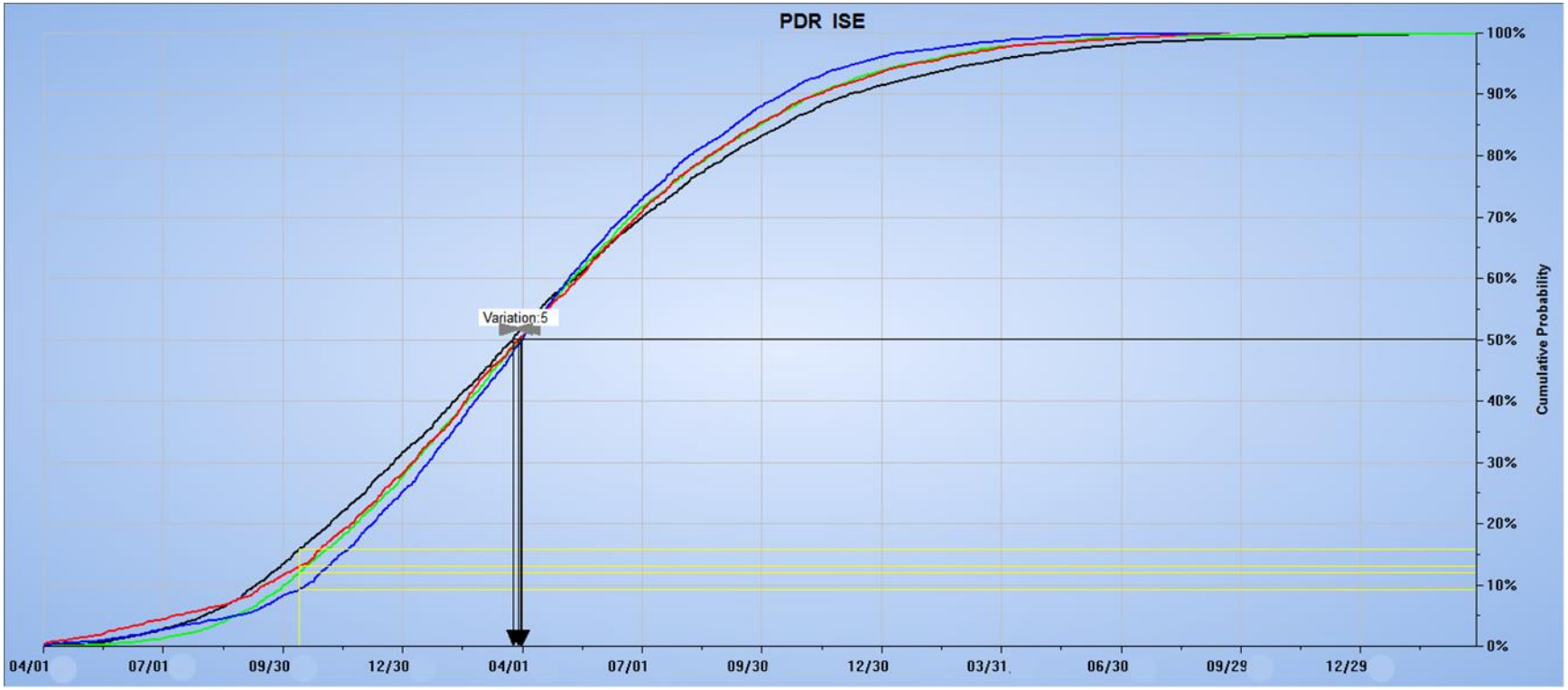
Comparative Analysis Stacked Bar Chart



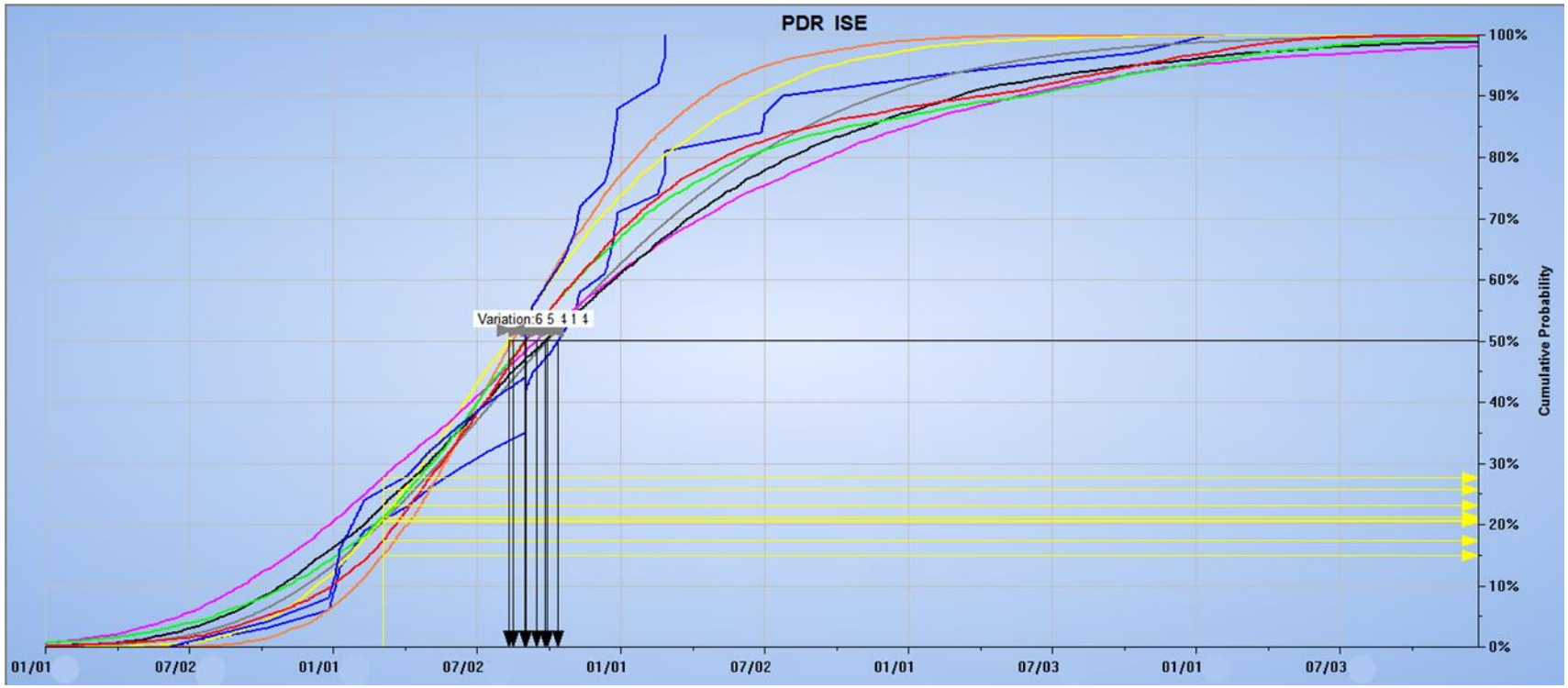
Simulation Results
CDR Milestone



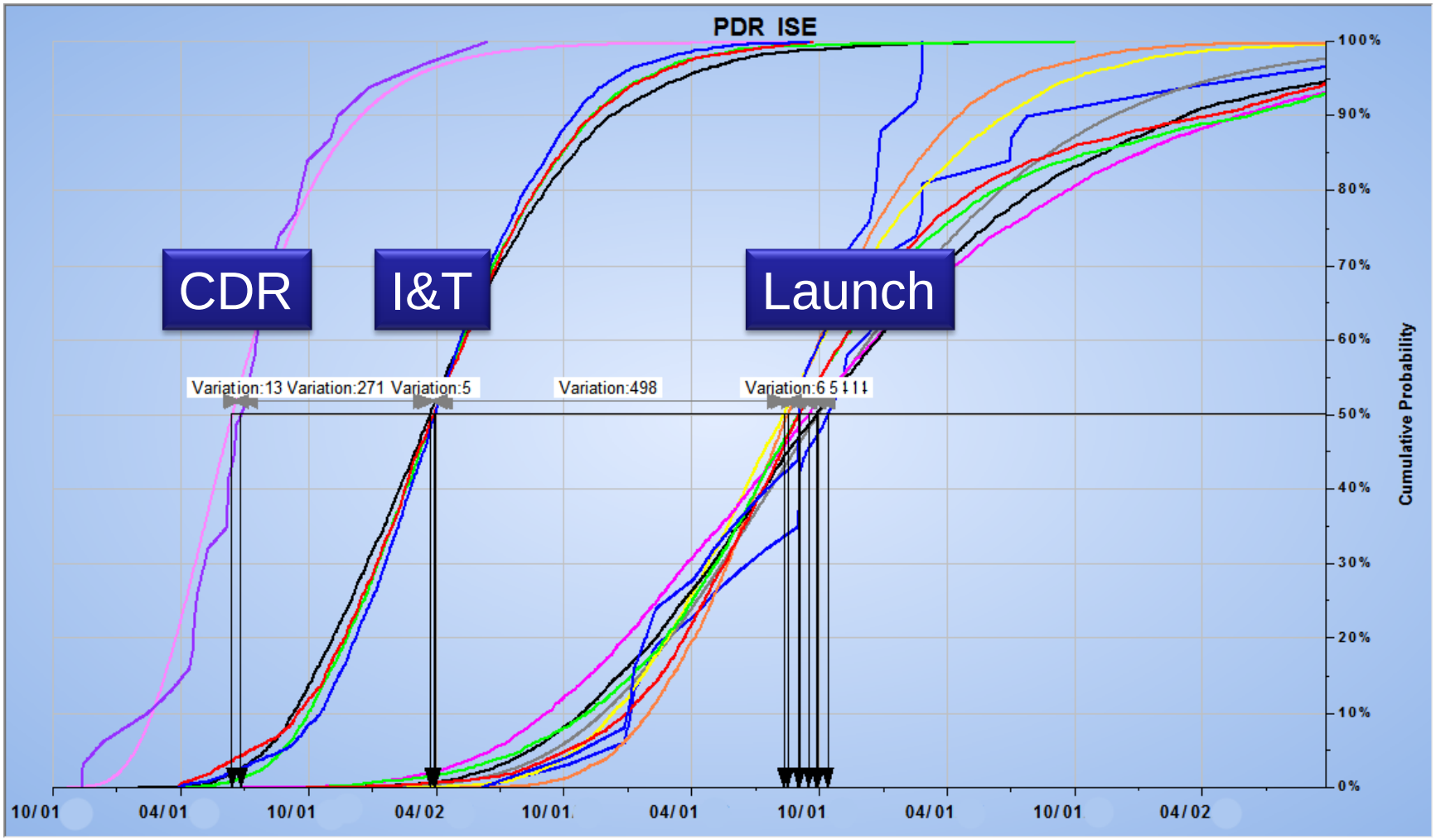
Simulation Results
I&T Start Milestone



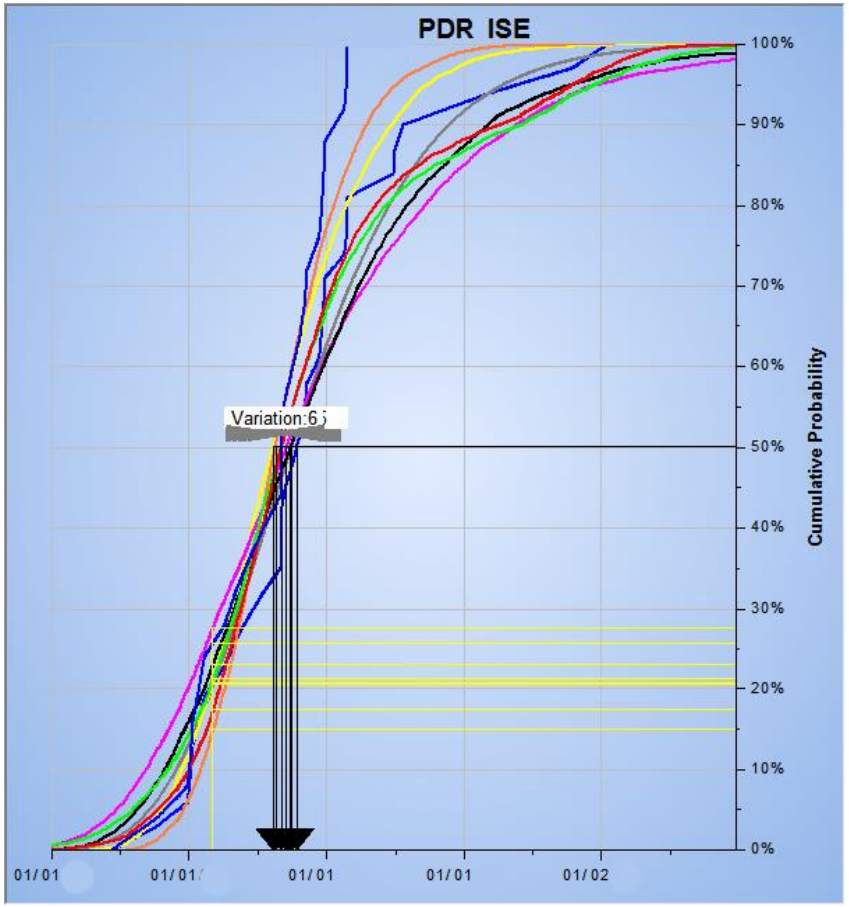
Simulation Results
Launch Date



Rolling Wave Chart



Executive Summary
S-Curve



- The ISE is a top-down estimate based on the average duration and variation of similar projects
- Various level 1 and level 2 schedule simulation models were developed
- Based on these ISE models, the likelihood of meeting the 3/##/## opening day of the launch window ranges from 15-28%
- The 50% confidence level launch readiness date ranges from 8/11/## to 10/13/##
- If nothing is done to maintain schedule, then based on historical data, the project could launch 5-7 months late
- However, the project must launch during the 20## opportunity or face a 26 month delay to the next opportunity
- Various mitigation strategies can be employed to compress the schedule to meet the launch window, including working overtime or additional shifts
- Additional shifts may require additional resources above the planned reserves.

CONCLUSIONS

Conclusions

- Historical data analysis can be used to estimate the schedule uncertainty for a new mission.
- Analysis and removal of outliers can improve the quality of probability distributions.
- Weak correlation exists between phases of a project.
- Uncertainty distributions can be applied to high-level summary models.
- Intermediate milestones can be predicted as well as launch date.
- Results are consistent across various types of models.